Nuclear Engineering and Technology xxx (2018) 1–15

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

An intelligent hybrid methodology of on-line system-level fault diagnosis for nuclear power plant

Min-jun Peng [a,*], Hang Wang [a], Shan-shan Chen [b], Geng-lei Xia [a], Yong-kuo Liu [a], Xu Yang [a], Abiodun Ayodeji [a,c]

[a] Key Subject Laboratory of Nuclear Safety and Simulation Technology, Harbin Engineering University, Harbin, Heilongjiang 150001, China
[b] Wuhan Second Ship Design and Research Institute, Wuhan, Hubei 430064, China
[c] Nuclear Power Plant Development Directorate, Nigeria Atomic Energy Commission, Abuja, Nigeria

ARTICLE INFO

Article history:
Received 2 June 2017
Received in revised form
26 November 2017
Accepted 28 November 2017
Available online xxx

Keywords:
Fault Diagnosis
Mahalanobis Distance
Multi-flow Model
Pressurized Water Reactor
Simulation Model

ABSTRACT

To assist operators to properly assess the current situation of the plant, accurate fault diagnosis methodology should be available and used. A reliable fault diagnosis method is beneficial for the safety of nuclear power plants. The major idea proposed in this work is integrating the merits of different fault diagnosis methodologies to offset their obvious disadvantages and enhance the accuracy and credibility of on-line fault diagnosis. This methodology uses the principle component analysis-based model and multi-flow model to diagnose fault type. To ensure the accuracy of results from the multi-flow model, a mechanical simulation model is implemented to do the quantitative calculation. More significantly, mechanism simulation is implemented to provide training data with fault signatures. Furthermore, one of the distance formulas in similarity measurement—Mahalanobis distance—is applied for on-line failure degree evaluation. The performance of this methodology was evaluated by applying it to the reactor coolant system of a pressurized water reactor. The results of simulation analysis show the effectiveness and accuracy of this methodology, leading to better confidence of it being integrated as a part of the computerized operator support system to assist operators in decision-making.

1. Introduction

The peaceful usage of nuclear energy can ease the world energy crisis and reduce environmental pollution, but there are potential radioactive dangers in nuclear power plants (NPPs). Engineering practice shows that when a malfunction occurs, misoperation and misdiagnosis by operators could result in catastrophic consequences for the immediate surroundings, and the trans-boundary effect of the spread of airborne radioactive materials could impact our global ecological environment [9]. Radioactive material leakage from an NPP in the Three Mile Island nuclear accident is a good illustration of the potential effect of an operator's lack of accurate judgment and incorrect measures taken after an accident. The occurrence of human error is due to the fact that numerous coupled subsystems will produce massive and scattered alarms after a malfunction [4]. Besides this, the tremendous psychological pressure that operators undergo during a novel nuclear transient situation cannot be over emphasized, and these factors make it difficult for operators to detect and diagnose faults in a timely manner [23]. Consequently, the development of effective fault diagnosis technology is essential to support operators to realize on time the root causes, locations, and degrees of faults. In this way, the safety and reliability of NPPs will be guaranteed [15].

The complex interaction of many components and the strong coupling of parameters in NPPs reduce the accuracy of traditional fault diagnostic methods that utilize thresholds to trigger alarms and to artificially diagnose faults [24]. Therefore, there have been numerous research efforts toward the implementation of automatic and intelligent fault diagnosis. Currently, these methods can be broadly divided into three groups: qualitative empirical models, data-driven models, and quantitative mathematical models [7]:

(1) Qualitative empirical models are among the most widely applied of these methodologies, especially for expert systems [14]. In reference to their merits, experience accumulated by experts from long-term practice is used to construct

* Corresponding author.
E-mail address: heupmj@163.com (M.-j. Peng).

https://doi.org/10.1016/j.net.2017.11.014

Please cite this article in press as: M.-j. Peng, et al., An intelligent hybrid methodology of on-line system-level fault diagnosis for nuclear power plant, Nuclear Engineering and Technology (2018), https://doi.org/10.1016/j.net.2017.11.014

knowledge database, so that complex quantitative models are avoided. However, if there is an excessive number of rules, problems such as matching conflicts, will occur during the reasoning process and lead to low efficiency (Soon, 1995). In addition, the evaluation of the degree of failure cannot be completed using qualitative models.

(2) Data-driven models are constructed by massive learning and training with historical data [17]. The advantage of this method is that the modeling processes are relatively simpler, more universal, and require smaller workload than other methods. Unfortunately, the data for many fault scenarios cannot be acquired in advance [20]. In addition, some of these methods are “black box” models, and this makes decision-making by the operator difficult [12]. Hence, a single data-driven method may lead to uncertainty, and the result may not be trusted by operators.

(3) Quantitative mathematical models are efficient in describing physical processes. As a result, the diagnosis results have a strong interpretability [21]. However, an NPP is a complex nonlinear system with control system regulation that could lead to relatively high inertia; therefore, it is difficult to build an accurate physical model for diagnosis. Indeed, building a quantitative model for diagnosis requires a heavy workload [24].

As mentioned previously, each single methodology has its own demerits; therefore, these methodologies cannot be used in isolation to detect and solve fault diagnosis issues effectively for NPP engineering application. Accordingly, different categories of methods are hybridized to solve fault diagnostic challenges. To end this, Hadad et al. [11] adopted a BP neural network and wavelet transform to diagnose system abnormalities. Gofuku [1] applied support vector machine and wavelet transform to detect process malfunctions. The University of Tennessee used the combination of principle component analysis (PCA) and causal reasoning to diagnose faults [29]. Chu et al. [3] at Harbin Engineering University studied Bayesian networks and used the multi-flow model (MFM) to eliminate uncertainty in fault diagnosis methods.

However, the hybrid methodologies aforementioned mainly used data-driven methods to reflect the relation between abnormal parameters and malfunctions by training and learning from sample data [16]. Then, qualitative empirical models are integrated to eliminate the weaknesses and reduce uncertainties in data-driven methods. These methods are indeed beneficial to the progress of fault diagnosis, but the diagnostic efficiency and accuracy are still below the requirements. Moreover, the acquisition of sample data for different failure modes is very limited in engineering applications. That is, as a result of limited available data with fault signatures, it is hard for data-driven methods to diagnose a fault accurately. In fact, training data with fault signatures can be simulated by on-line simulation models, thereby reducing the demerits of data-driven methods. Recent advancements in simulation technologies have improved the performance of quantitative model-based methods, and accurate quantitative mathematical models can now be achieved. A faster-than-real-time simulator, TOKRAC, for calculating postaccident thermal–hydraulic behavior in the primary system of a pressurized water reactor (PWR) plant has been proposed by Gofuku et al. [2]; however, the secondary thermal–hydraulic side and the control system of the PWR are simplified, which may not be true during the monitoring and diagnosis processes. Currently, parts of the on-line simulation model that are mainly focused on the reactor core have been used in America, France, and Canada [26]. Westinghouse Company developed a system called BEACON that can do OMDP. In addition, the Idaho National Laboratory [10] first proposed the idea of predicting the situations of NPPs by using advanced nuclear thermal-hydraulic and control simulation models.

This research work adopts a reactor coolant system (RCS) of a PWR to evaluate the proposed hybrid fault diagnosis methodology. The originality and advantageous features of this study are summarized as below:

- The architecture of hybrid fault diagnosis technology is first proposed. The advantages of knowledge-based methods, quantitative mathematical models, and data-driven methodologies are enhanced by organic integration, and their demerits are dexterously compensated for.
- Thermal–hydraulic simulation model is adopted with consideration of detailed node partitioning for RCS, sensibility and significance of related auto-control system, and on-line data updating for real-time tracking of the PWR.
- By combining the simulation model and PCA to detect residual errors of corresponding measured and simulated parameters, malfunctions in the NPP can be detected more rapidly and distinguished from calculation errors of the simulation model.
- The MFM, which belongs to the qualitative reasoning methods, is used to diagnose the fault types. More practically, for operation support, rules and failure modes in the knowledge database and modeling of the MFM are separated, which makes it easy for operators to modify the rules without rebuilding the MFM.
- The Mahalanobis distance technique is integrated to evaluate failure degree. Compared with neural networks and many other classification algorithms, the Mahalanobis distance is a cluster algorithm that is suitable for fault degree assessment. In addition, the on-line nature of the proposed method eliminates over-reliance of the diagnostic procedures on large off-line training data.

The structure of this article is as follows: The theories and methodologies are introduced in Section 2. The development and modeling of a hybrid fault diagnosis system is presented in Section 3. In Section 4, analysis and comparison of the simulation results are presented. The methodology is summarized in Section 5.

2. Theory of hybrid fault diagnosis methods

2.1. Structure of hybrid fault diagnosis methods

The purpose of hybrid fault diagnosis is to use the advantages of each method to compensate for the shortcomings of other methods, so that accuracy and credibility can be ensured. The MFM is efficient for causal reasoning and explanation and is hence suitable to discriminate failure types. However, matching conflicts may occur during reasoning processes, and the results may not be exclusive. At this point, quantitative mathematical simulation models will be involved in the mechanism to analyze the quantitative relationship between parameters and malfunctions. Therefore, the results of qualitative models will be independently verified. After locating the failure type, the degree of failure should be evaluated for certain typical faults to assist the operators to execute further actions. As the rates of change of the measured parameters for different failure degrees are all different, distance functions in similarity measurements can be used to achieve data mining and classification. Meanwhile, the quantitative simulation model can perform faster-than-real-time calculation to make up for the lack of sample data. The specific research route is shown in Fig. 1 and is delineated as follows:

Please cite this article in press as: M.-j. Peng, et al., An intelligent hybrid methodology of on-line system-level fault diagnosis for nuclear power plant, Nuclear Engineering and Technology (2018), https://doi.org/10.1016/j.net.2017.11.014